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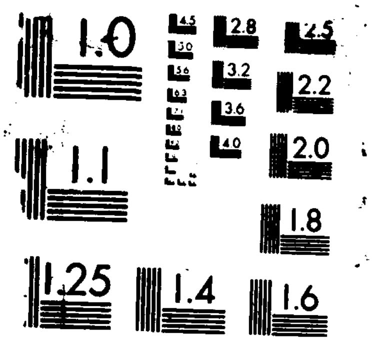

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Communications Research Centre

THE CHARACTERISTICS OF TWO BROADBAND (2 MHz TO 10 MHz) SWITCHED VEE ANTENNAS

by

G.M. Royer

This work was sponsored by the Department of National Defence, Research and Development Branch under Project No. 0414V11.

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OTTAWA, JANUARY 1987

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DEPARTMENT OF COMMUNICATIONS
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THE CHARACTERISTICS OF TWO BROADBAND (2 MHz TO 10 MHz) SWITCHED VEE ANTENNAS

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(Radar and Communications Technology Branch)

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CHARACTERISTICS FOR TWO BROADBAND
(2 MHZ to 10 MHZ) SWITCHED VEE
ANTENNAS

by

G.M. ROYER

ABSTRACT

The characteristics of many antennas were investigated and evaluated against the general specification listed below. This document presents the properties of the two (switched vee) antennas which were judged to be best suited for the application.

Specification #1: The antenna is to serve as components for a 2 MHz to 10 MHz communications system where the signal's propagation path includes one reflection from the ionosphere and the transmitter and receiver are separated by about 100 km or less.

Specification #2: The antenna's construction is to be such as to make it as easy, as is practical, to change the system's site.

1. INTRODUCTION

It follows from the mode of propagation indicated in the Abstract's specification #1, that the antenna's gain should be greatest (and without deep nulls) for θ angles (see Fig. 1) between 0° and about 30°.

A specific specification, which is in partial fulfillment of the Abstract's general specification #2, is that the heights of antenna towers should not be greater than 15 meters.

Figures 1 and 14 show the geometries of the two antennas whose characteristics we will be examining. Their half lengths are 84 meters and 46 meters and we will therefore refer to them as 84 meter, and 46 meter, switched vee antennas. The switches shown are used to change the antenna's effective length and hence divide its overall bandwidth into sub-bands. Switch positions which give successively longer antenna lengths are those which produce successively lower frequency sub-bands. Section 2 contains the theory which shows how the switches are located, along the antenna wires, to produce sub-bands with closely related electrical properties.

Lowering the antenna wires for the purpose of manually repositioning the switches would be inconvenient. It should however be possible to develop switches whose positions could be changed electrically. The system could include switch control wires inside an outer shielding conductor. The RF signal currents would be forced to stay on the outer

surface of the shielding conductor through the use of low pass filters on the control wires. Another possible system would employ battery operated switches and circuitry where the batteries and circuitry are located on the antenna near the switches. The switches would be activated from a remote location through the use of a coded light or infra-red beam. It can be seen that the switched vee antenna gives simplicity of construction, with a view to satisfying the Abstract's specification #2, at the expense of the electrical complexity associated with the switches.

A length of transmission line between an antenna's terminals and its tuning unit (the unit which matches the antennna's input impedance to the characteristic impedance of the transmission line from the transmitter or receiver) will increase the rate of change (with respect to frequency) of antenna impedance as seen at tuning unit. The longer the transmission line the larger the above effect. One of the advantages enjoyed by switched vee antennas is that their geometry makes it possible to connect the antenna's terminals directly to the tuning unit which, in turn, can be anchored securely to the ground.

The Method of Moments[2] computer program Numerical Electromagnetic Code-version 3 (NEC-3) was used to compute the antenna electrical characteristics contained in this report's graphs and tables. Over the years, many individuals have contributed to the development of NEC. The modifications which produced version 3 were made by G.J. Burke [1] at the Lawrence Livermore National Laboratory.

2. DEFINITION OF VARIABLES AND DERIVATION OF EQUATIONS USED TO COMPUTE ANTENNA LENGTHS

The electrical properties of the antennas will be characterized using the following parameters.

Z_a = the impedance seen at the antenna's input terminal

$= R_a + jX_a$

$G_\theta(\theta,\phi)$ = the θ polarized gain of the antenna in the direction (θ,ϕ) (see Fig. 1 for the definition of θ and ϕ).

$G_\phi(\theta,\phi)$ = the ϕ polarized gain of the antenna in the direction (θ,ϕ)

$G(\theta,\phi)$ = the total gain of the antenna in the direction (θ,ϕ)

The antenna's θ polarized gain is that associated with the θ polarized field. For example when the antenna is used to transmit (as distinguished from receive) a signal then

$$G_\theta(\theta,\phi) = \frac{4\pi r^2 S_\theta(r,\theta,\phi)}{P_a} \qquad \ldots(1)$$

$$S_\theta(r,\theta,\phi) = \frac{|E_\theta(r,\theta,\phi)|^2}{\eta} \qquad \ldots(2)$$

η = the intrinsic impedance for free space (air)

$\approx 376.73\ \Omega$

$E_\theta(r,\theta,\phi)$ = the far-field component of the antenna's electric field intensity (volts/m), at (r,θ,ϕ), which is polarized parallel to the θ unit vector.

$S_\theta(r,\theta,\phi)$ = the part of the far-field power density (watts/m^2), for the transmitted signal, which is associated with the θ polarized electric field intensity ($E_\theta(r,\theta,\phi)$).

P_a = the signal power into the antenna's input terminal.

Note, that by far-field E_θ and S_θ we mean that the range (r) from the antenna to the field point is sufficiently large such that G_θ does not change significantly as r is increased. $G_\phi(\theta,\phi)$ is defined as in eqns. (1) and (2) except that E_θ and S_θ are replaced by respectively E_ϕ

(far-field ϕ polarized electric field intensity) and S_ϕ. The antenna's total gain is defined to be

$$G(\theta,\phi) = \frac{4\pi r^2 S(r,\theta,\phi)}{P_a} \qquad \text{...(3)}$$

$$S(r,\theta,\phi) = S_\theta(r,\theta,\phi) + S_\phi(r,\theta,\phi) \qquad \text{...(4)}$$

$S(r,\theta,\phi)$ = the total far-field power density for the transmitted signal at (r,θ,ϕ).

In other words

$$G(\theta,\phi) = G_\theta(\theta,\phi) + G_\phi(\theta,\phi) \qquad \text{...(5)}$$

The XY plane in Figs. 1 and 14 forms the top surface of an homogenous, non-magnetic (its permeability (μ) is that for free space (μ_0)), ground. The dielectric properties of a non-magnetic dielectric can be specified by its relative permeability (ε_r) where

$$\varepsilon_r = \varepsilon/\varepsilon_0 = \varepsilon_r' - j\varepsilon_r'' \qquad \text{...(6)}$$

ε = the permittivity (Ω^{-1}sec) of the dielectric

ε_0 = the permittivity of free space

ε_r' = the real part of the relative permittivity

ε_r'' = the imaginary part of the relative permittivity

In this document we will follow standard practice and use ε_r' and σ to characterize the ground's dielectric properties where

$$\varepsilon_r'' = \frac{\sigma}{\omega\varepsilon_0} \qquad \text{...(7)}$$

σ = the ground's conductivity (Ω^{-1}/m or mhos/meter)

$\omega = 2\pi f$

f = signal frequency (Hz)

Note that, when the ground is not perfectly conducting, the power density functions at field points near the ground plane do not vary as $1/r^2$ (even when r is very large); therefore the antenna gains near the ground plane are functions of r. The antenna gains which appear in this document's figures and tables were computed using fields given by NEC-3 at r = 10,000 m. This range is large enough such that near-ground power densities have been attenuated sufficiently to put the corresponding antenna gains below the scale employed in this document's figures; hence the portions of the gain functions shown are for practical purposes independent of r.

Consider the special case, shown in Fig. 1, where there are three switches/leg and let the switch positions listed in Table 1 divide the antenna's overall frequency bandwidth into four frequency bands. If a) to d) below were true then scaling theory and the relationships expressed by eqns.(8) to (13) would ensure that the antenna's electrical characteristics (input impedance and gain) would vary (with respect to scaled frequency) the same way across each of the frequency sub-bands.

a) Antenna wires and ground-perfectly conducting.

b) Feed dimensions and separation of feed from the ground plane-very small with respect to other antenna dimensions and signal wavelength.

c) The portion of the antenna beyond the open switches closest to the feed - negligibly effect the antenna's electrical characteristics.

d) The diameter of the antenna wires - tapered linearly with respect to distance from the feed.

$$\ell_2/\lambda_2 = \ell_1/\lambda_1 \qquad \dots (8)$$

$$\ell_2/\lambda_3 = \ell_1/\lambda_2 \qquad \dots (9)$$

$$\ell_3/\lambda_3 = \ell_1/\lambda_1 \qquad \dots (10)$$

$$\ell_3/\lambda_4 = \ell_1/\lambda_2 \qquad \dots (11)$$

$$\ell_4/\lambda_4 = \ell_1/\lambda_1 \qquad \dots (12)$$

$$\ell_4/\lambda_5 = \ell_1/\lambda_2 \qquad \dots (13)$$

λ_1 and λ_2 are the longest and shortest signal wavelengths in the longest wavelength sub-band

λ_2 and λ_3 are the longest and shortest signal wavelengths in the second longest wavelength sub-band

etc.

$\ell_1 \rightarrow \ell_4$ specify the antenna's leg length and locate the switches (see Fig. 1).

When eqns. (8) to (13) are combined, it is found that

$$\lambda_2 = [\lambda_1{}^3\lambda_5]^{\frac{1}{4}} \qquad \text{...(14)}$$

$$\lambda_3 = [\lambda_1{}^2\lambda_5{}^2]^{\frac{1}{4}} \qquad \text{...(15)}$$

$$\lambda_4 = [\lambda_1\lambda_5{}^3]^{\frac{1}{4}} \qquad \text{...(16)}$$

$$\ell_2 = [\lambda_5/\lambda_1]^{\frac{1}{4}}\ell_1 \qquad \text{...(17)}$$

$$\ell_3 = [\lambda_5/\lambda_1]^{2/4}\ell_1 \qquad \text{...(18)}$$

$$\ell_4 = [\lambda_5/\lambda_1]^{\frac{3}{4}}\ell_1 \qquad \text{...(19)}$$

Since signal frequency and wavelength are related by

$$\lambda = c/f \qquad \text{...(20)}$$

c = the speed of signal propagation in free space (air)

the above equations can be written as follows

$$f_2 = [f_1{}^3f_5]^{\frac{1}{4}} \qquad \text{...(21)}$$

$$f_3 = [f_1{}^2f_5{}^2]^{\frac{1}{4}} \qquad \text{...(22)}$$

$$f_4 = [f_1f_5{}^3]^{\frac{1}{4}} \qquad \text{...(23)}$$

$$\ell_2 = [f_1/f_5]^{\frac{1}{4}}\ell_1 \qquad \text{...(24)}$$

$$\ell_3 = [f_1/f_5]^{2/4}\ell_1 \qquad \text{...(25)}$$

$$\ell_4 = [f_1/f_5]^{\frac{3}{4}}\ell_1 \qquad \text{...(26)}$$

It can be shown that in general

$$f_n = [f_1^{N+1-n} f_{N+1}^{n-1}]^{1/N}, \ n = 1 \rightarrow N+1 \qquad \text{...(27)}$$

$$\ell_n = [f_1/f_{N+1}]^{(n-1)/N} \ell_1 \ , \ n = 1 \rightarrow N \qquad \text{...(28)}$$

N = the number of sub-bands (which makes N-1 the number of switches per antenna leg).

n = sub-band number for $n = 1 \rightarrow N$

f_1 and f_{N+1} are respectively the lower and upper bounds on the antenna's overall bandwidth (respectively 2 MHz and 10 MHz for the antennas studied in this document).

f_n and f_{n+1} are respectively the lower and upper frequency bounds for sub-band n.

The scheme expressed by eqns. (27) and (28) was used to determine the switch locations and sub-band frequency bounds for the antennas investigated in this document. The resulting antenna electrical characteristics were found to be acceptably alike across each of the sub-bands. This is true despite the fact that the previously listed conditions a) to d) are either, not satisfied, or only approximately satisfied. In particular:

1) For some cases the ground will not be perfectly conducting; this makes the grounds dielectric properties frequency sensitive (see eqn. (7)).

2) Condition b) is approximately met.

3) The portion of the antennas beyond the open switch closest to the feed seems to have little effect on the antenna's properties.

4) The diameter of the wires will be made to be .23 cm, and is therefore not tapered linearly with respect to distance from the feed.

3. THE CHARACTERISTICS OF AN 84 METER SWITCHED VEE ANTENNA

The geometry and coordinate systems associated with the N = 4, 84 meter, switched vee antenna, which we will be investigating in this section, are contained in Fig. 1. For each sub-band number (n), Table 1 lists switch positions and locations (ℓ_n); and the minimum, mean and maximum sub-band frequencies.

Let us first consider how the antenna's gain properties change as the angle α (see Fig. 1) is varied. Figures 2a to 2f contain sets of vertical, total gain patterns (at the middle frequency of the n = 1 sub-band) for values of α ranging from 0° to 75° where the ground (whose top surface is the XY plane) is considered to by perfectly conducting. Note, it follows from the symmetry of the antenna's geometry that:

a) When $\alpha = 0°$, the gain functions are even, with respect to ϕ, about 0°, 90°, 180° and -90°; therefore it is sufficient to consider the antenna's gain characteristics for ϕ angles between 0° and 90°.

b) When $\alpha = 0°$, the gain functions are even, with respect to ϕ, about 90° and -90°; therefore it is sufficient to consider the antenna's gain properties for ϕ angels from -90°, through 0°, to 90°.

It is shown in Fig. 2 that, when $\alpha = 0°$, the $\phi = 0°$ beamwidth is much narrower than that when $\phi = 90°$. As α is increased (and the antenna's aperture parallel to the $\phi = 0°$ plane is decreased) the $\phi = 0°$ beamwidth broadens. When $\alpha = 45°$, and for θ less than about 50°, Fig. 2d shows the gain to be approximately omnidirectional as a function of ϕ. It can be seen therefore that if, as regards coverage, the antenna user has no preference with respect to azimuth direction then the choice of 45° for α would be appropriate. The 84 meter vee antenna characteristics presented in the remainder of this section are for the case where $\alpha = 45°$.

Figures 3 to 5 plot input impedance ($Z_a = R_a + jX_a$) versus frequency, for Fig. 1's antenna, where $\alpha = 45°$ and the ground is perfectly conducting. In Fig. 3 (where the switches have been set as appropriate for the n = 1 sub-band) we plot Z_a versus f over a sufficiently wide range of frequencies to illustrate how the leg length (ℓ_1) has been chosen to locate the n = 1 sub-band between the antiresonant frequencies at 1.72 MHz and 3.48 MHz. Note that when an antenna is antiresonant there is a current null located at the antenna's feed point. This makes Z_a very large. For dipole-like antennas, antiresonant frequencies occur when the antenna's leg length is about $\lambda/2$, λ, $3\lambda/2$, etc. The above 1.72 MHz and 3.48 MHz frequencies are respectively the antenna's $\lambda/2$ and λ antiresonant frequencies when n = 1. Refer next to Figs. 4 and 5 and let us compare the antenna's input impedance properties for the n = 1 and n = 4 sub-bands. It can be seen that across the two sub-bands:

a) The input reactance (X_a) variation is much the same.

b) The shapes of the input resistance (R_a) functions are much alike however the, n = 4, R_a function is displaced upward with respect to that where n = 1.

The above mentioned characteristic wherein the R_a function is displaced upward as n is increased is probably caused by the fact that the antenna's feed is located 1 meter above the ground plane. This increases the separation, in wavelengths, between the ground plane and the active part of the antenna as n increases. Note that when a horizontal, or approximately horizontal, antenna is located less than about $\lambda/4$ above the ground plane then, the closer the antenna to the ground plane, the less is the antenna's input resistance. Antennas whose radiation resistance is low tend to be inefficient (low gain). Unfortunately the 15 m restriction on tower height puts the active part of the antennas considered in this document, at a height above the ground plane which is significantly less than $\lambda/4$.

Fig. 2's total gain patterns were for the mean frequency in the n = 1 sub-band. Fig. 6 contains total gain patterns for the minimum, mean and maximum frequencies in the n = 3 sub-band where $\alpha = 45°$ and the ground is perfectly conducting. It can be seen that (although there is some variation of G with respect to f) the antenna's total gain for $\theta < 50°$ is approximately ϕ omnidirectional for frequencies across the band. Comparison of Figs. 2d and 6b indicates that, when the ground is perfectly conducting, the antenna's gain properties are nearly the same in all bands.

Throughout most of this document, the gain characteristic which we will investigate is total gain which, as shown by eqn. (6), is the sum of the antenna's θ and ϕ polarized gains. To see typical examples of how the switched vee antenna's total gain is divided between its θ and ϕ polarized gains compare:

a) Fig. 2a with Fig. 7 for the case where $\alpha = 0°$ and n = 1

b) Fig. 6b with Fig. 8 for the case where $\alpha = 45°$ and n = 3

It is generally true for the switched vee antenna that:

1) When $\alpha = 0°$, $G_\theta = 0$ when $\theta = 90°$ or $-90°$ and $G_\phi = 0$ when $\phi = 0$ or 180°

2) When $\alpha = 0°$, $G_\theta = 0$ when $\theta = 90°$ or $-90°$

With the exception of Figs. 9 and 10 and 11a, the antenna characteristics presented in the report are for the case where there are no supporting towers (or for what is almost equivalent where the supporting towers are made of a non-conducting material such as fibreglass). Some idea of the effect of supporting towers at the extreme outer ends of the legs of Fig. 1's antenna ($\alpha = 45°$, ground perfectly conducting) can be seen by comparing the following figures:

1) Fig. 9 with Fig. 2d where f = 2.4953 MHz in the n = 1 sub-band.

2) Fig. 10 with Fig. 6b where f = 5.5798 MHz in the n = 3 sub-band.

3) Fig. 11a with Fig. 11b where f = 4.63 MHz in the n = 3 sub-band.

The diameter and height of the towers employed to obtain Figs. 9, 10 and

11a were respectively .3 m and 14.9 m. We chose 4.63 MHz as one of the frequencies at which to look at the effect of supporting towers on the antenna's gain characteristics because at this frequency the towers' heights are $.23\lambda$. It is shown in Figs. 4 and 5 of reference 3 that towers with the diameters employed here (.3 m) are resonant and have very high scattering cross sections when their heights are $.23\lambda$. The above Fig. 4 also shows a strong scattering resonance for towers whose heights are about $.75\lambda$. This resonance is of no concern to us here however because it would occur well above our highest frequency of interest (10 MHz) at about 15 MHz. When the total gain pattern in the figures listed above under 1) to 3) are compared, it is seen that the towers effect the antenna's gain characteristics; the effects however do not appear (for our purposes) to be deleterious.

Table 2 lists key values for input impedance and antenna gain for all four sub-bands of Fig. 1's antenna where the ground is perfectly conducting and $\alpha = 45°$. Note that: a) the minimum value for R_a in a sub-band, corresponds very closely to the R_a (at mean f) values listed, and b) $G(0,\phi)$ is the antenna's total gain in the direction $\theta = 0$ (vertical to the ground plane).

Through the remainder of this section we will be looking at the characteristics of Fig. 1's antenna with $\alpha = 45°$ and where the ground is not perfectly conducting.

Fig. 12 plots Z_a as a function of f in the n = 1 sub-band where $\alpha = 45°$ and the grounds dielectric properties are $\epsilon_r' = 15$ and $\sigma = .008\ \Omega^{-1}/m$. The above conductivity is typical for land in temperate regions (see reference 4 page 638). When Figs. 4 and 12 are compared it is seen that the imperfectly conducting ground: a) had little effect on X_a, and b) significantly increased R_a. Note that the above increase in R_a is typical for antennas near an imperfectly conducting ground plane because the power computed to be absorbed by R_a has, in addition to the power radiated into the half space above the ground plane, a component representing the power which is absorbed in the ground.

Fig. 13 contains three sets of vertical total gain patterns at the minimum, mean and maximum frequencies in the n = 3 sub-band where $\alpha = 45°$, $\epsilon_r' = 15$ and $\sigma = .008\ \Omega^{-1}/m$. When the above gain patterns are compared with those in Fig. 6 (for which the ground is perfectly conducting) it is seen that the finitely conducting ground significantly reduces the antenna's gain. The loss of antenna gain due to the presence of an imperfectly conducting ground can be attributed to two phenomena; i.e. that due to absorption by the ground: 1) as the signal propagates over it, and 2) in the vicinity of the antenna. The phenomenon under 1) above occurs within a few wavelengths of the ground and produces a gain function (when defined as for example in eqn. 4) which is a function of range. The phenomenon listed under 2) above does not effect gain as a function of range and predominates for θ angles which locate the field point more than a few wavelengths above the ground plane. The reduction of gain evidenced by Fig. 13 is of the type listed above under 2), and could therefore be greatly reduced by laying a conducting screen, on top of the ground, in the vicinity of the antenna.

Tables 3 to 5 list the same key values as appear in Table 2, for the Fig. 1's antenna where $\alpha = 45°$ and the ground's dielectric properties are respectively: a) $\varepsilon_r' = 15$, $\sigma = .030\ \Omega^{-1}/m$. b) $\varepsilon_r' = 15$, $\sigma = .008\ \Omega^{-1}/m$, and c) $\varepsilon_r' = 7$, $\sigma = .001\ \Omega^{-1}/m$. Comparison of the information shows that:

a) Over the range of ground dielectric properties considered, there was little effect on the antenna's input reactance.

b) There were significant effects on the antenna's, input resistance (which went up), and gain (which went down), as the ground's conductivity (σ) was reduced to $.001\ \Omega^{-1}/m$.

Table 1, Switch positions and parameters associated with the frequency sub-band number (n) for Fig. 1's 84 m switched vee antenna.

n	Switched Position	ℓ_n (m)	f_n (MHz)	$(f_n+f_{n+1})/2$ (MHz)	f_{n+1} (MHz)
1	A,B,C - closed	84.00	2.0000	2.4953	2.9907
2	A,B - closed; C - open	56.17	2.9907	3.7314	4.4721
3	A - closed, B, C - open	37.57	4.4721	5.5798	6.6874
4	A,B,C - open	25.12	6.6874	8.3437	10.000

Table 2, Input impedance and vertical gain characteristics for Fig. 1's 84 m switched vee antenna where α = 45° and the ground is considered to be perfectly conducting.

n	$Z_a(\Omega)$ at min. f	$R_a(\Omega)$ mean f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	mean f	max. f
1	71.6+j(-1834)	28.2	57.0+j(650)	7.60	7.28	6.42
2	81.2+j(-1747)	34.0	84.5+j(657)	7.80	7.50	6.96
3	89.5+j(-1677)	37.5	95.1+j(651)	7.87	7.27	6.68
4	101+j(-1602)	42.5	109+j(645)	8.03	7.10	6.24

Table 3, Input impedance and vertical gain characteristics for Fig. 1's antenna where $\alpha = 45°$ and the ground's dielectric properties are $\epsilon_r' = 15$ and $\sigma = .030\ \Omega^{-1}/m$.

n	$Z_a(\Omega)$ at min. f	$R_a(\Omega)$ mean f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	mean f	max. f
1	152+j(-1755)	61.3	138+j(709)	4.47	3.88	2.35
2	170+j(-1663)	70.1	174+j(707)	4.67	4.24	3.28
3	187+j(-1590)	76.0	189+j(690)	4.65	4.03	2.92
4	207+j(-1517)	82.6	204+j(666)	4.81	3.92	2.41

Table 4, Input impedance and vertical gain characteristics for Fig. 1's antenna where $\alpha = 45°$ and the ground's dielectric properties are $\epsilon_r' = 15$ and $\sigma = .008\ \Omega^{-1}/m$.

n	$Z_a(\Omega)$ at min. f	$R_a(\Omega)$ mean f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	mean f	max. f
1	214+j(-1701)	86.1	198+j(735)	3.03	2.31	0.50
2	241+j(-1612)	97.8	236+j(717)	3.13	2.58	1.37
3	265+j(-1547)	104	246+j(683)	3.02	2.32	1.07
4	286+j(-1491)	107	247+j(645)	3.13	2.33	0.84

Table 5, Input impedance and vertical gain characteristics for Fig. 1's antenna where α = 45° and the ground's dielectric properties are ε_r' = 7 and σ = .001 Ω^{-1}/m.

n	$Z_a(\Omega)$ at min. f	$R_a(\Omega)$ mean f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	mean f	max. f
1	376+j(-1622)	138	297+j(736)	0.65	-.19	-2.10
2	393+j(-1561)	141	313+j(701)	0.82	0.32	-1.04
3	397+j(-1518)	136	302+j(662)	0.86	0.39	-.90
4	393+j(-1476)	130	285+j(623)	1.15	0.74	-.73

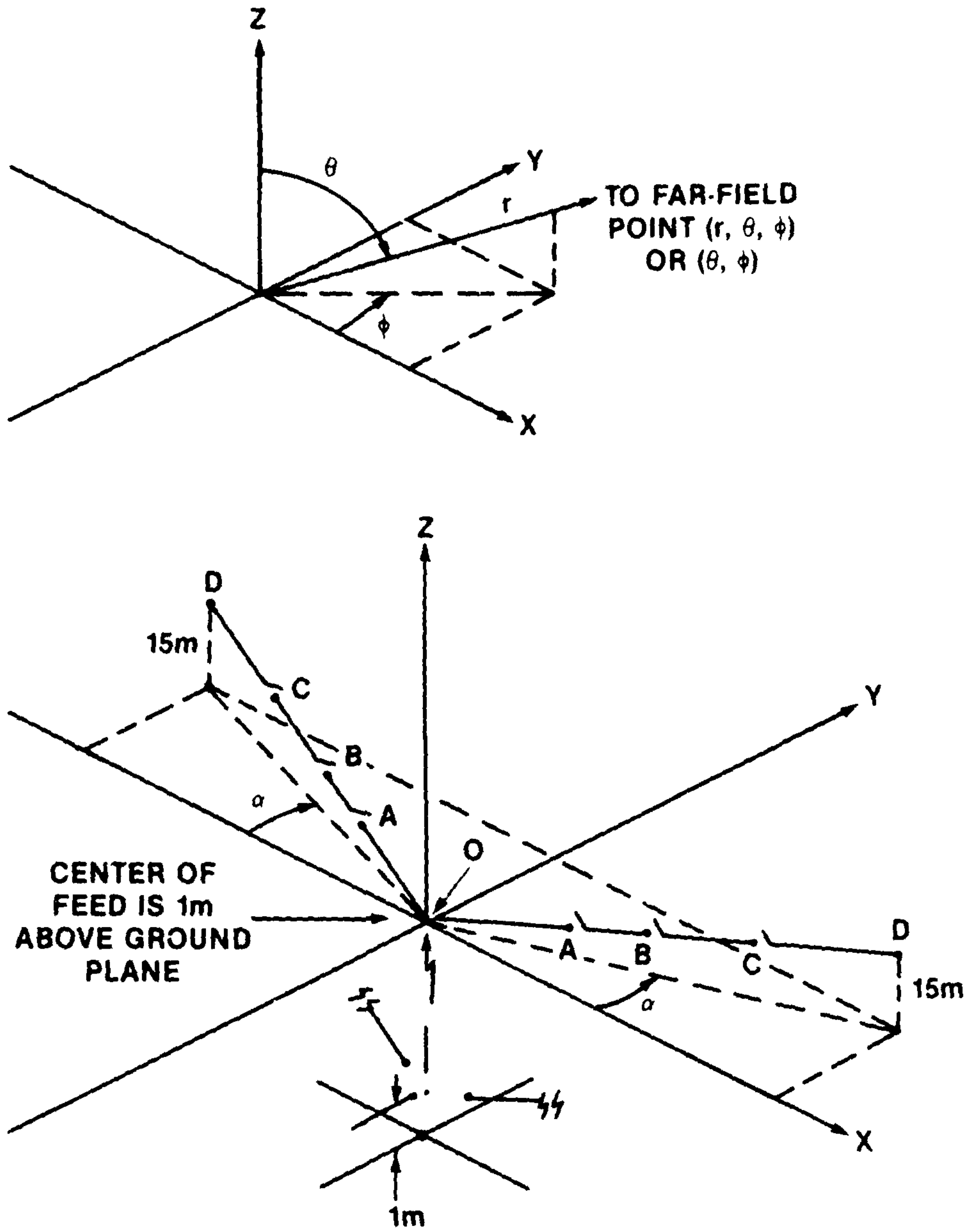


Fig. 1, Geometry associated with an 84 m switched vee antenna for the case where N = 4. The antenna wire lengths are; $\ell_1 = \ell_{OD} = 84.00$ m, $\ell_2 = \ell_{OC} = 56.17$ m, $\ell_3 = \ell_{OB} = 37.57$ m and $\ell_{OA} = \ell_4 = 25.12$ m. Antenna wire diameter = .23 cm. The top surface of the ground is coincident with the XY plane.

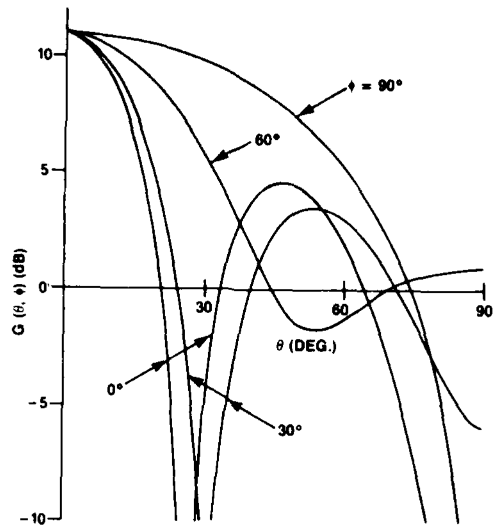


Fig. 2a, α = 0°

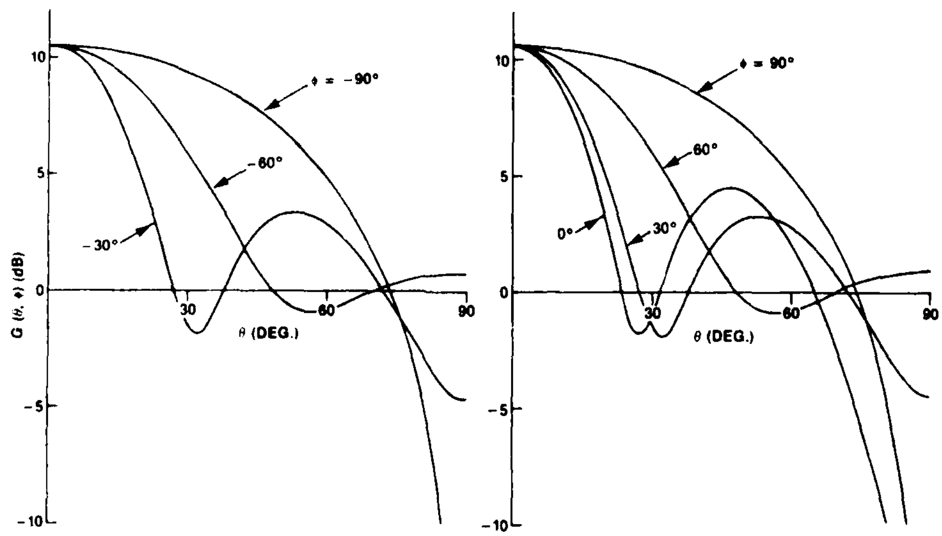


Fig. 2b, α = 15°

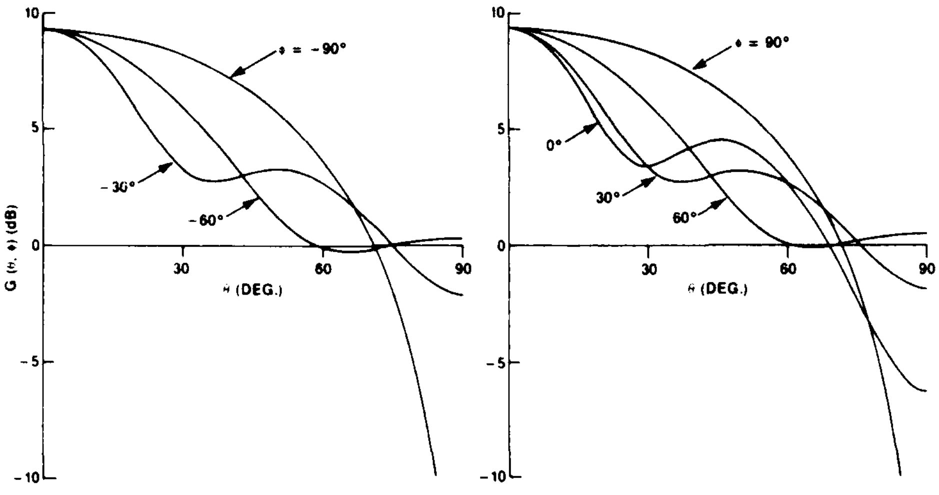


Fig. 2c, α = 30°

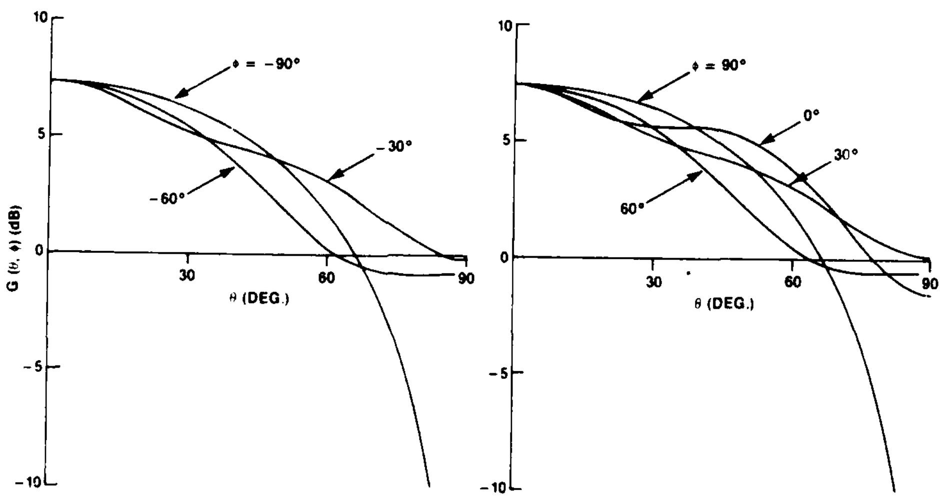


Fig. 2d, α = 45°

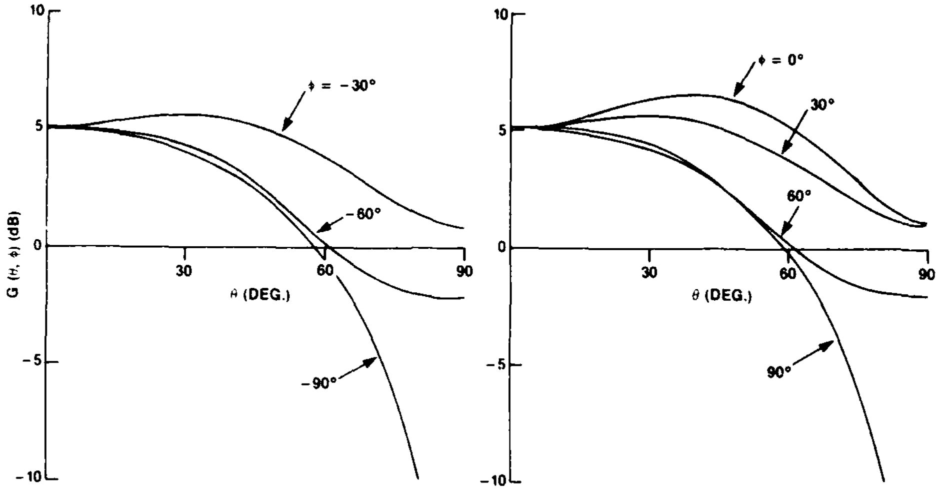


Fig. 2e, α = 60°

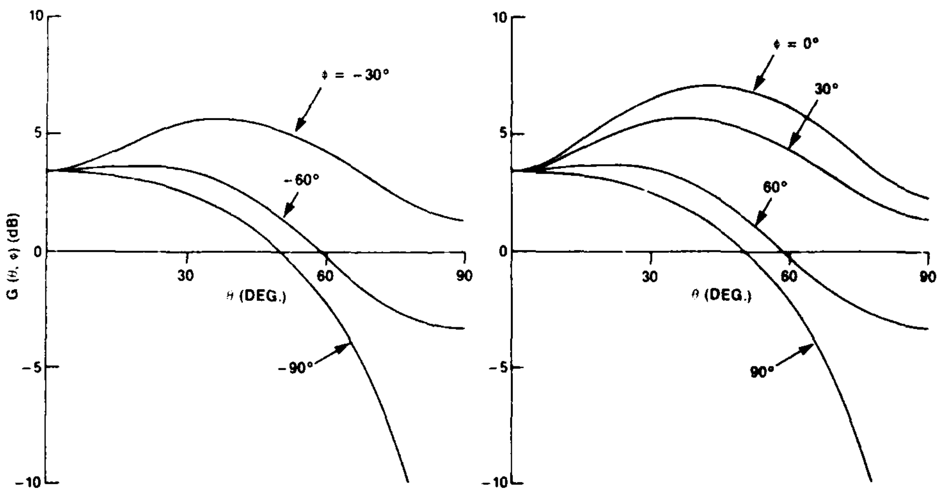


Fig. 2f, α = 75°

Fig. 2, Vertical gain patterns as a function of α for Fig. 1's antenna where f = 2.4953 MHz in the n = 1 frequency sub-band and the ground is perfectly conducting.

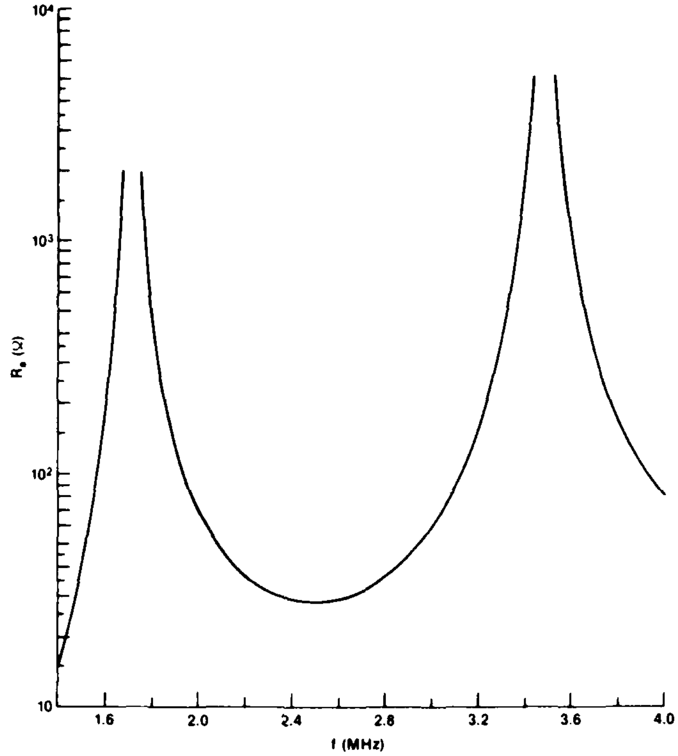


Fig. 3a, Input resistance (R_a)

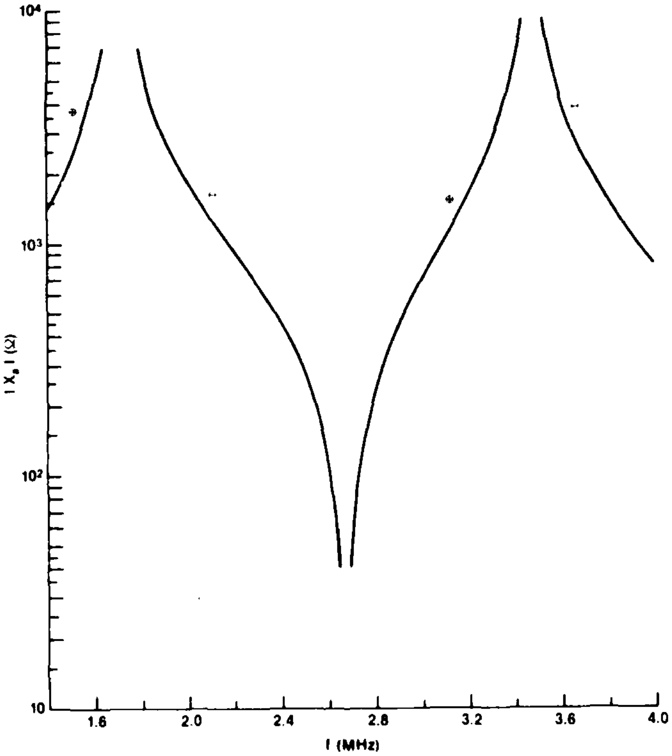


Fig. 3b, Input reactance (X_a)

Fig. 3, Input impedance ($Z_a = R_a + jX_a$) for Fig. 1's antenna where $\alpha = 45°$, the ground is considered to be perfectly conducting and the antenna switches are in the n = 1 condition (see Table 1).

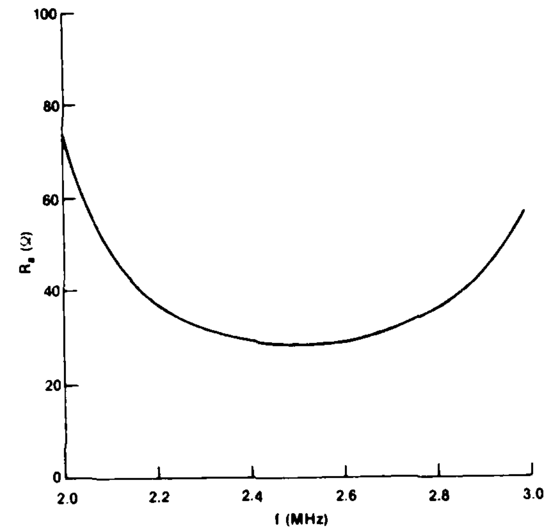


Fig. 4a, Input resistance (R_a)

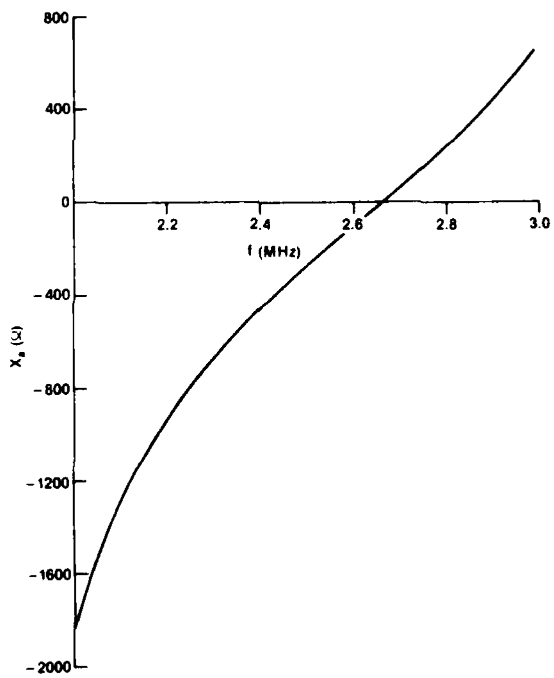


Fig. 4b, Input reactance (X_a)

Fig. 4, Input impedance ($Z_a = R_a + jX_a$), for Fig. 1's antenna, across the n = 1 frequency sub-band where $\alpha = 45°$ and the ground is perfectly conducting.

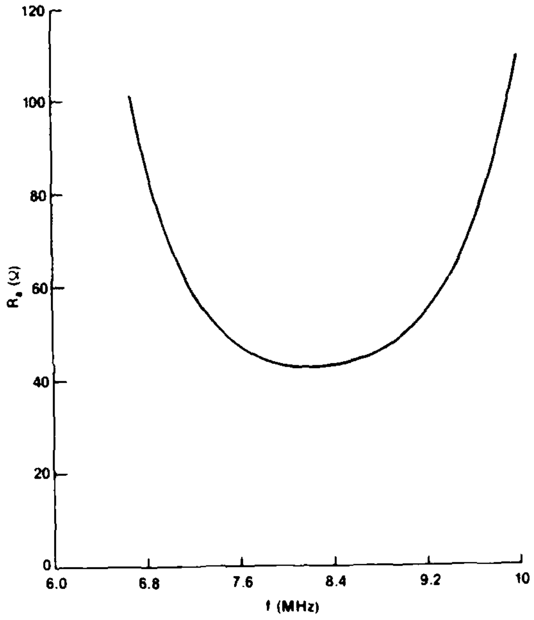


Fig. 5a, Input resistance (R_a)

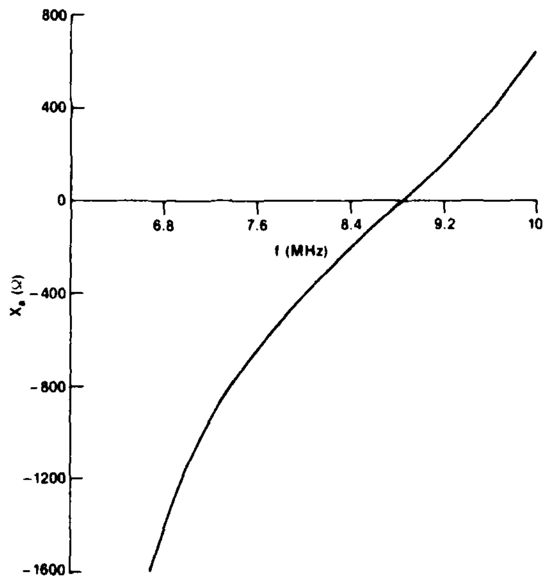


Fig. 5b, Input reactance (X_a)

Fig. 5, Input impedance ($Z_a = R_a + jX_a$), for Fig. 1's antenna, across the n = 4 frequency sub-band where $\alpha = 45°$ and the ground is perfectly conducting.

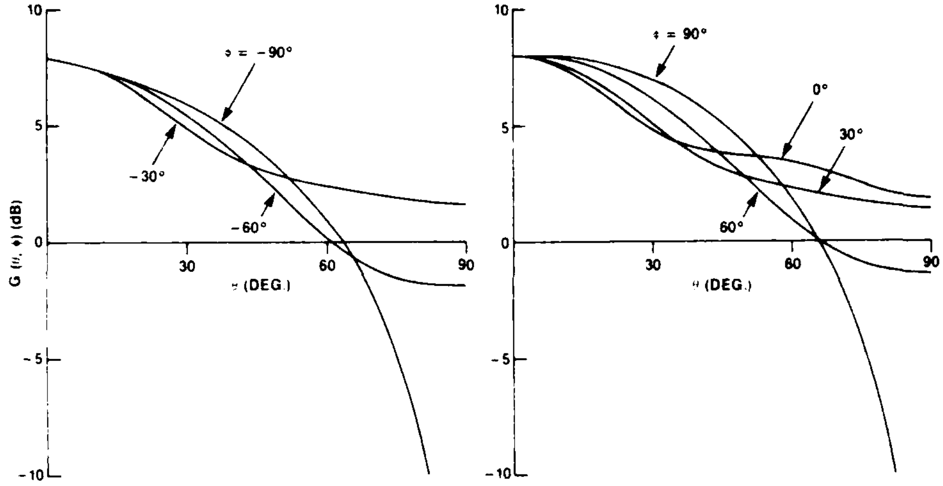


Fig. 6a, f = 4.4721 MHz

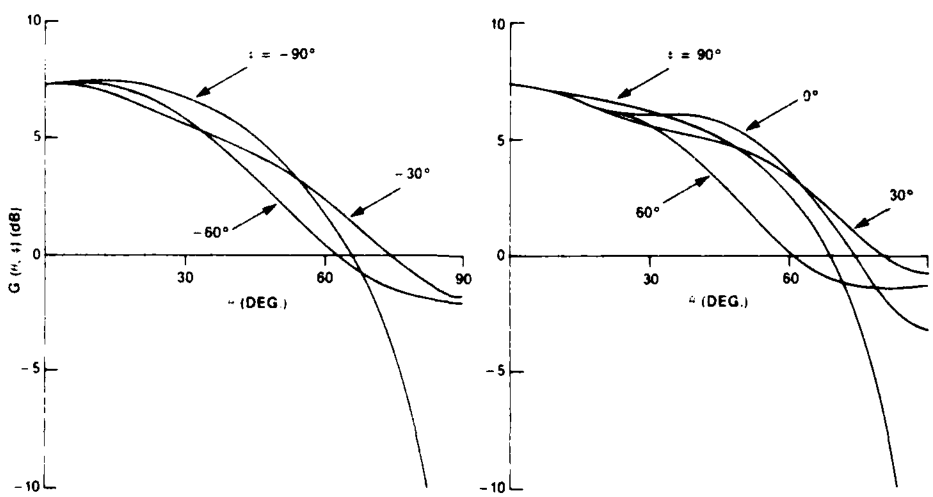


Fig. 6b, f = 5.5798 MHz

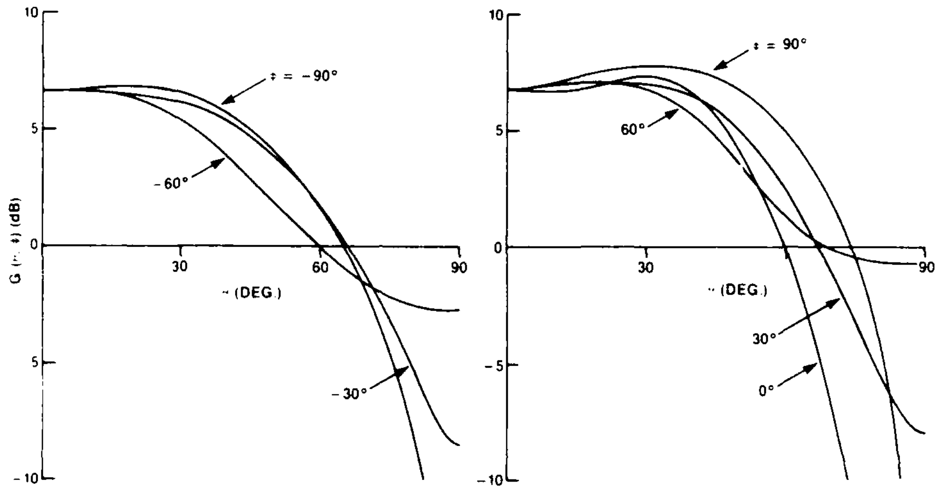


Fig. 6c, f = 6.6784 MHz

Fig. 6, Vertical total-gain patterns at the minimum, mean and maximum frequencies in the n = 3 frequency sub-band for Fig. 1's antenna where α = 45° and the ground is perfectly conducting.

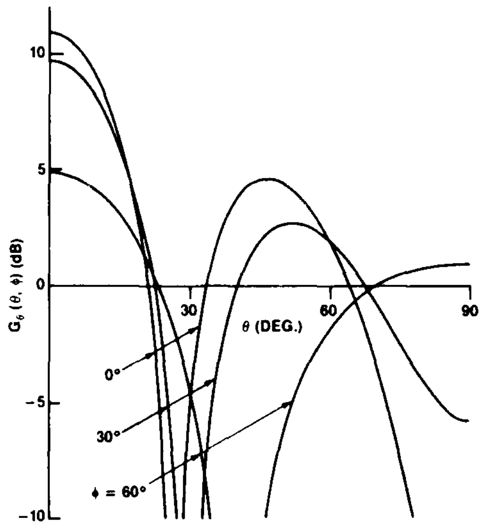


Fig. 7a, θ = polarized gain

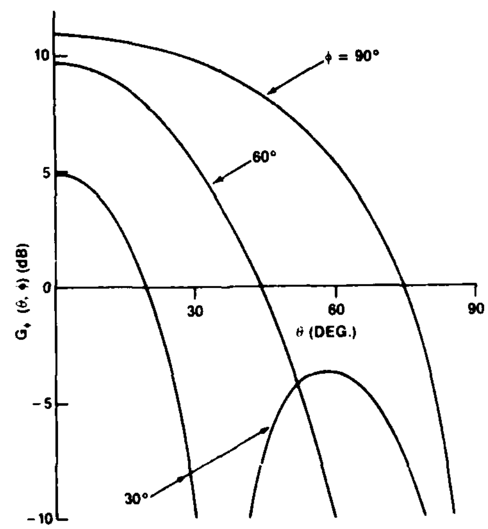


Fig. 7b, ϕ = polarized gain

Fig. 7, θ and ϕ polarized gain patterns for Fig. 1's antenna where f = 2.4953 MHz in the n = 1 frequency sub-band, α = 0°, and the ground is perfectly conducting.

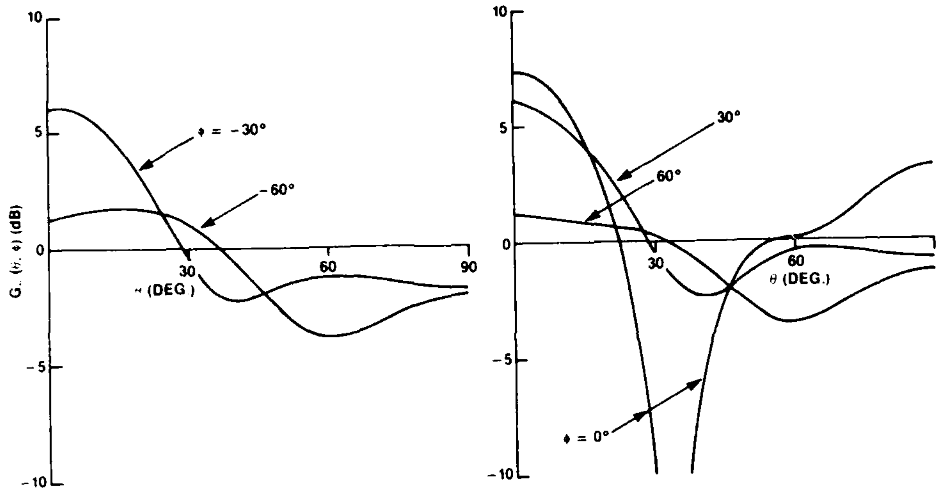


Fig. 8a, θ = polarized gain

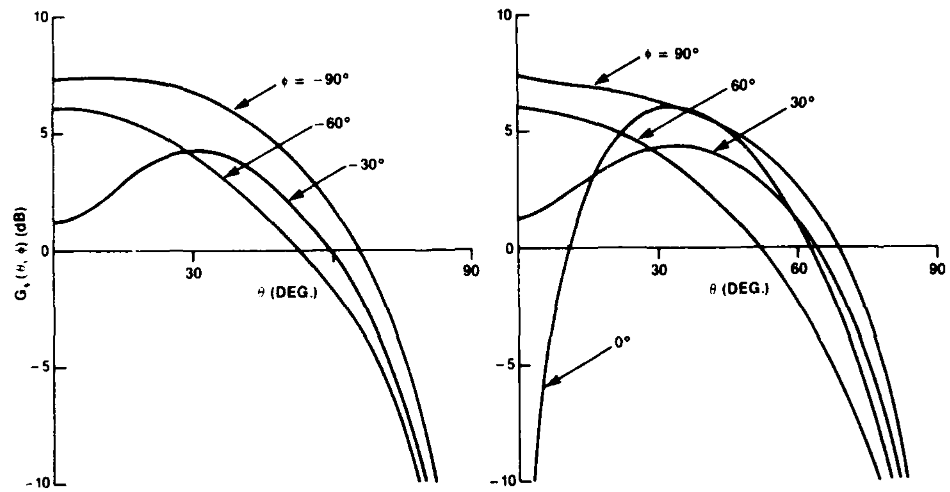


Fig. 8b, ϕ = polarized gain

Fig. 8, θ and ϕ polarized gain patterns for Fig. 1's antenna where f = 5.5798 MHz in the n = 3 frequency sub-band, α = 45° and the ground is perfectly conducting.

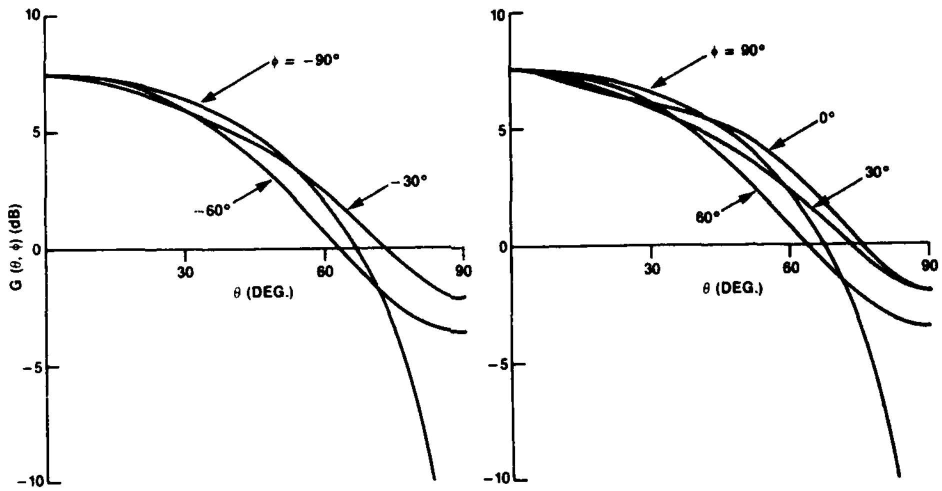


Fig. 9, Vertical total-gain patterns for Fig. 1's antenna with 14.9 m towers at the antenna's extreme ends where $\alpha = 45°$, f = 2.4953 MHz in the n = 1 frequency sub-band and the ground is perfectly conducting (compare with Fig. 2d).

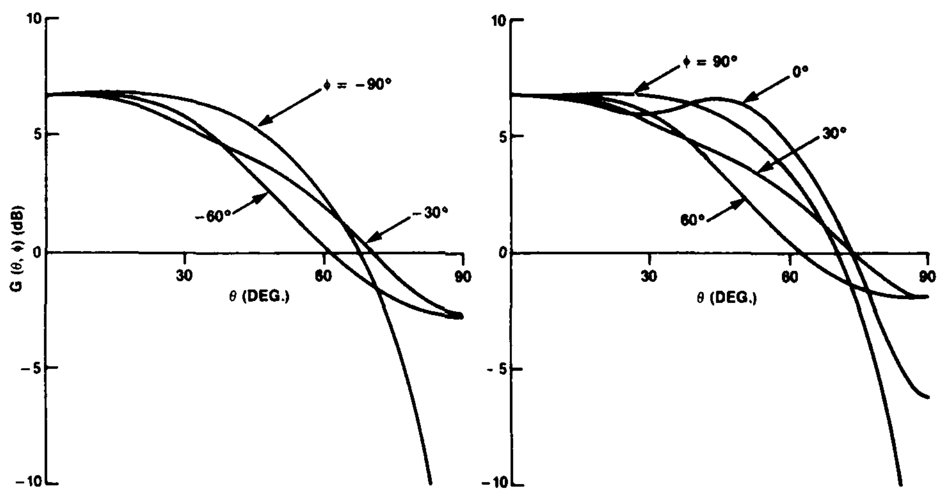


Fig. 10, Vertical total-gain patterns for Fig. 1's antenna with 14.9 m towers at the antenna's extreme ends where $\alpha = 45°$, f = 5.5798 MHz in the n = 3 frequency sub-band and the ground is perfectly conducting (compare with Fig. 6b).

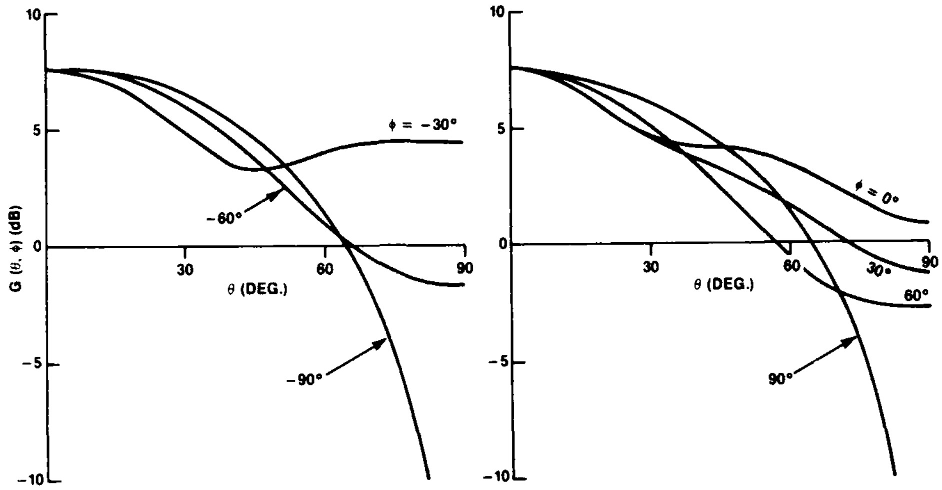


Fig. 11a, 14.9 m towers at the antenna's extreme ends.

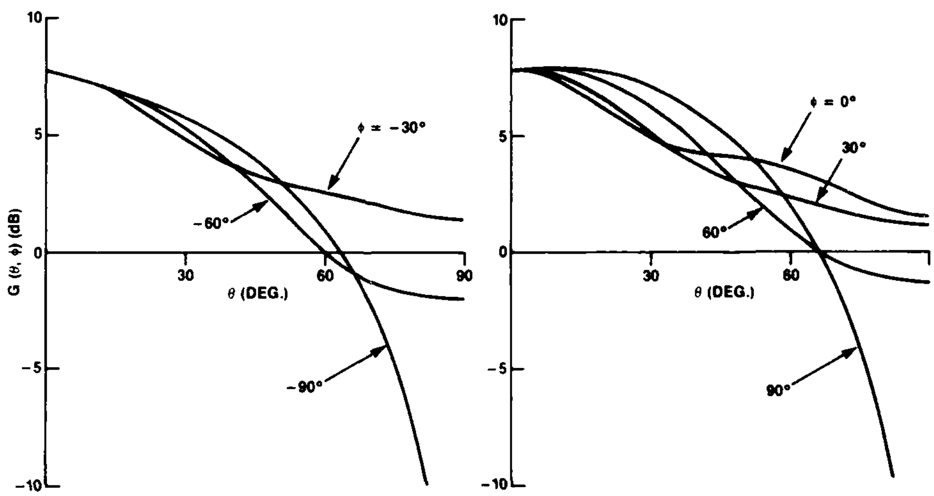


Fig. 11b, No towers at the antenna's extreme ends.

Fig. 11, A comparison of total-gain patterns for Fig. 1's antenna a) with, and b) without towers at the antenna's extreme ends where $\alpha = 45°$, $f = 4.63$ MHz (tower height = $.23\lambda$) in the $n = 3$ sub-band and the ground is perfectly conducting.

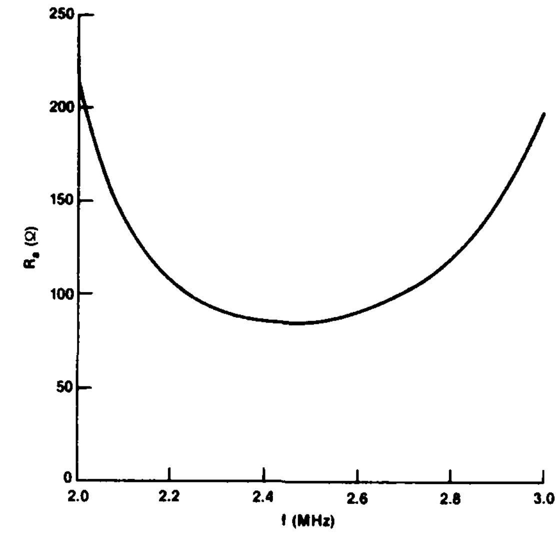


Fig. 12a, Input resistance (R_a)

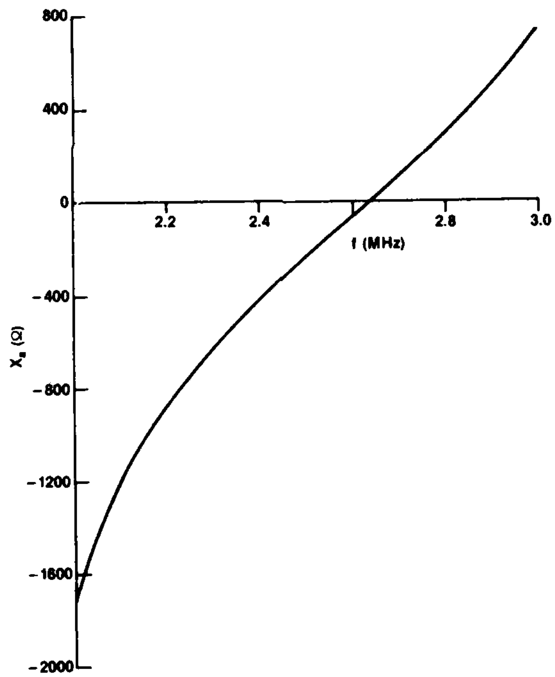


Fig. 12b, Input reactance (X_a)

Fig. 12, Input impedance ($Z_a = R_a + jX_a$), for Fig. 1's antenna, across the n = 1 frequency sub-band where $\alpha = 45°$ and the ground's dielectric properties are $\epsilon_r' = 15$ and $\sigma = .008\ \Omega^{-1}/m$.

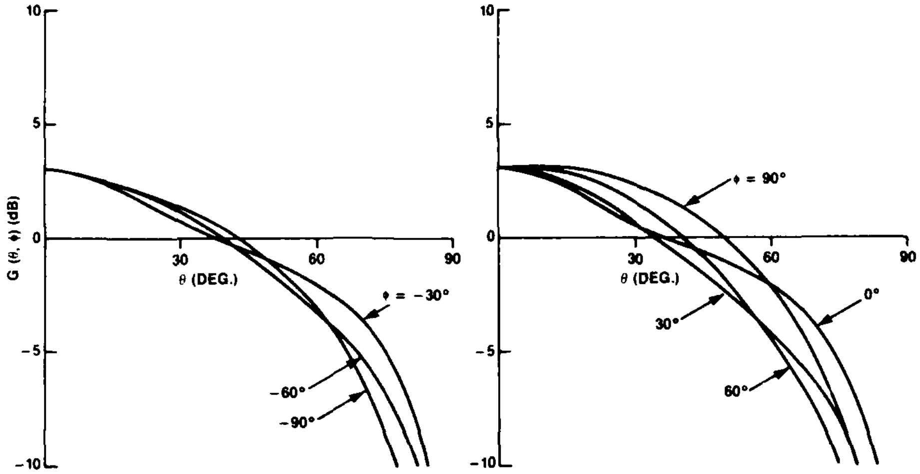


Fig. 13a, f = 4.4721 MHz

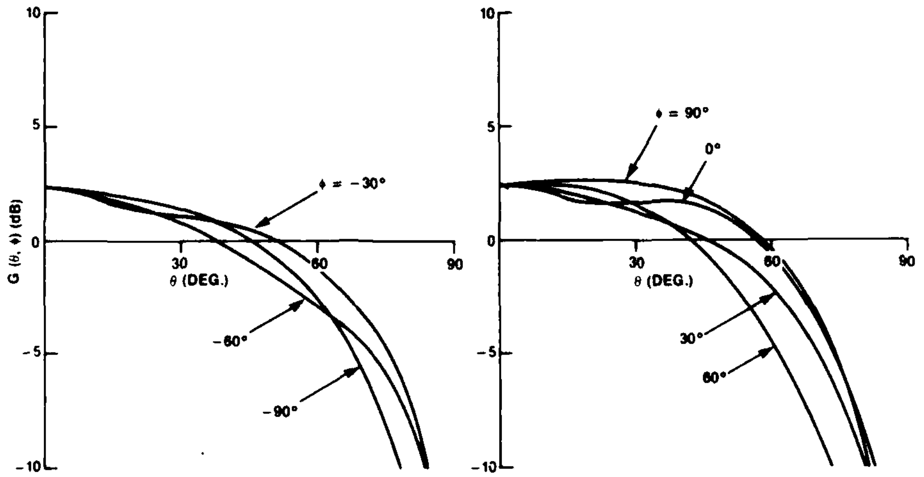


Fig. 13b, f = 5.5798 MHz

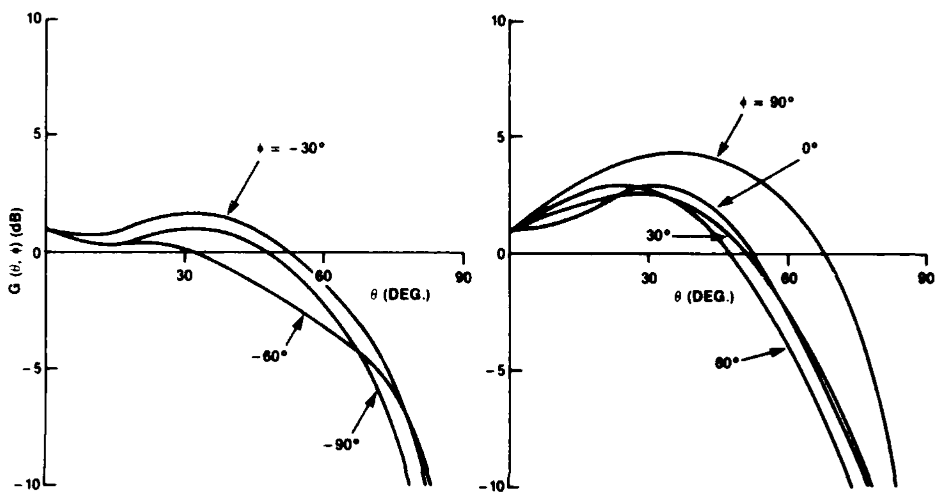


Fig. 13c, f = 6.6874 MHz

Fig. 13, Vertical total-gain patterns at the minimum, mean and maximum frequencies in the n = 3 frequency sub-band for Fig. 1's antenna where α = 45° and the ground's dielectric properites are ϵ_r' = 15 and σ = .008 Ω^{-1}/m.

4. THE CHARACTERISTICS OF A 46 METER SWITCHED VEE ANTENNA

Fig. 14 shows the geometry and coordinate systems associated with the N = 5, 46 meter switched vee antenna which we will be investigating in the section. The above choice of N and ℓ_1 are such that, across each sub-band, the frequency is always below that which would produce the $\lambda/2$ antiresonant condition. Table 6 lists, switch positions and locations (ℓ_n); and the minimum, mean and maximum sub-band frequencies.

One of the problems associated with an antenna like that shown in Fig. 14, where operation is below the $\lambda/2$ antiresonant frequency, is that as frequency is decreased, R_a rapidly drops to a small value (there is no minimum like that shown in Fig. 3a, for the 86 m antenna). It is not desirable that R_a be too small because, when R_a is small and decreased, the losses (in the antenna tuning unit, antenna wires and ground plane) increase with respect to the power radiated; hence decreasing the antenna's efficiency. The length ℓ_1 for Fig. 14's antenna was chosen by computing, at 2 MHz, the antenna's input impedance (Z_a) (where all switches were closed, $\alpha = 0°$ and the ground was considered to be perfectly conducting) for various values of ℓ_1 and selecting a length which gave an input resistance of about 10 Ω. A value of 46 m for ℓ_1 was found to be appropriate. Fig. 15 plots Z_a as a function of f (2 MHz < f < 3 MHz) for Fig. 14's antenna where all switches are closed (n = 1), $\alpha = 0°$ and the ground is perfectly conducting. Marked on Fig. 15 are the maximum frequencies, in the n = 1 sub-band, for the cases where N = 4 and N = 5 (see Tables 1 and 6). It can be seen that when N = 4, $Z_a \approx 3600 + j\ 8600$ Ω at the sub-band's maximum frequency. This is a high value, particularly as concerns the resistive component, because the antenna tuning unit must transform it to the characteristic resistance of a transmission line (probably 50 Ω). A value for N of 5 was therefore chosen for the antenna which we investigate in this section. This means that the antenna has 5 sub-bands and N - 1 = 4 (as shown in Fig. 14) switches/leg.

For the case where the ground is perfectly conducting Figs. 16 and 17 show how the gain and input impedance properties for Fig. 14's antenna vary as a function of α. It can be seen that increasing α:

1) Slightly broadened the $G(\theta,0°)$ 3 db beamwidth from 40° when $\alpha = 0°$ to 52° when $\alpha = 50°$

2) Decreased the antenna's input resistance and (as would be expected) when α became large enough made the antenna behave like a non-radiating two-wire transmission line.

As a consequence of the above behaviour the remainder of this section is devoted to the study of Fig. 14's antenna for the case where $\alpha = 0°$.

The sets of vertical total gain patterns in Figs. 18 and 19 (where $\alpha = 0°$ and the ground is perfectly conducting) in respectively the n = 1 and n = 3 sub-bands, show that there is very little change in the gain characteristics of Fig. 14's antenna either across a sub-band or from sub-band to sub-band.

A comparison of Figs. 19 and 20 illustrates the effect of an imperfectly conducting ground on the antenna's gain characteristics. The same general comments apply here as appear in the preceding section where Fig. 13 is discussed. Note that the ground reduces the gain, at the sub-band's minimum frequency, more than at its maximum frequency. The reason for this behaviour can be seen if we divide the power into the antenna (P_a) into two components as follows

$$P_a = I_a^2 R_r + I_a^2 R_g \qquad \ldots(29)$$

where the antenna's input resistance is

$$R_a = R_r + R_g \qquad \ldots(30)$$

I_a = the signal current at the antenna's feed

$I_a^2 R_g$ = signal power absorbed in the ground

$I_a^2 R_r$ = the power which escapes into the half space above the ground plane (i.e. the power not absorbed in the ground).

The resistance R_g and R_r are the parts of the antenna's input resistance which are associated (as shown above) with respectively the power absorbed in the ground plane and the power radiated (or not absorbed in the ground plane). The power $I^2 R_r$ is expended to produce the total far-field power density $S(r,\theta,\phi)$ in eqn. 3. Examination of eqns. (3) and (29) shows that the smaller R_r is with respect to R_g, then the smaller $S(r,\theta,\phi)$ will be with respect to P_a, and hence the less the total gain $(G(\theta,\phi))$. Fig. 15a indicates that R_r (when the ground is perfectly conducting $R_g = 0$ hence $R_a = R_r$) is low at the low frequency end of the sub-bands. It is not surprising therefore that an imperfectly conducting ground reduces the gain, for Fig. 14's antenna, more at the minimum than at the maximum frequency in a sub-band.

Table 6, Switch positions and parameters associated with the frequency sub-band numbers (n) for Fig. 14's 46 m switched vee antenna.

n	Switched Position	ℓ_n (m)	f_n (MHz)	$(f_n+f_{n+1})/2$ (MHz)	f_{n+1} (MHz)
1	A,B,C,D - closed	46.00	2.0000	2.3797	2.7595
2	A,B,C - closed; D - open	33.34	2.7595	3.2834	3.8073
3	A,B - closed; C,D - open	24.16	3.8073	4.5302	5.2531
4	A - closed; B,C,D - open	17.51	5.2531	6.2504	7.2478
5	A,B,C,D - open	12.69	7.2478	8.6239	10.000

Table 7, Input impedance and vertical gain characteristics for Fig. 14's 46 m switched vee antenna where $\alpha = 0°$ and the ground is considered to be perfectly conducting.

n	$Z_a(\Omega)$ at min. f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	max. f
1	9.63+j(373)	267+j(2603)	8.34	8.79
2	10.8+j(372)	305+j(2592)	8.52	8.96
3	12.2+j(371)	345+j(2568)	8.71	9.13
4	14.1+j(371)	401+j(2554)	8.90	9.22
5	17.2+j(375)	493+j(2562)	9.01	9.37

Table 8, Input impedance and vertical gain characteristics for Fig. 14's 46 m switched vee antenna where $\alpha = 0°$ and the ground's dielectric properties are $\epsilon_r' = 15$ and $\sigma = .030\ \Omega^{-1}/m$.

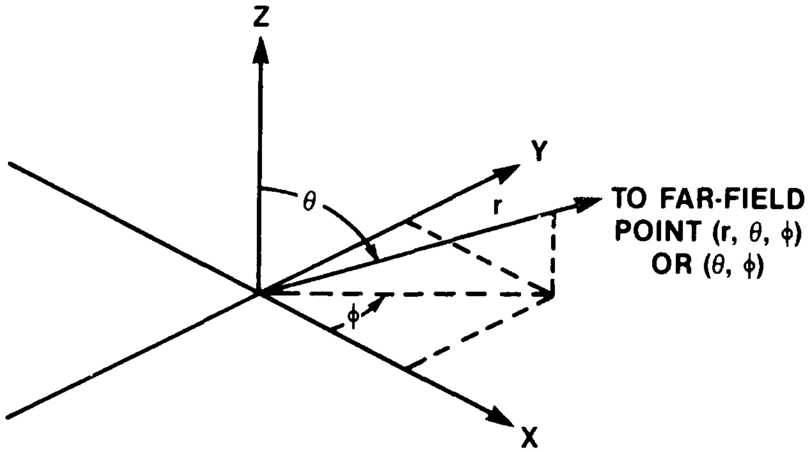
n	$Z_a(\Omega)$ at min. f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	max. f
1	37.7+j(402)	522+j(2713)	3.44	6.65
2	41.4+j(402)	600+j(2692)	3.76	6.80
3	45.1+j(401)	675+j(2645)	4.13	6.93
4	49.4+j(400)	762+j(2588)	4.56	7.02
5	55.0+j(400)	875+j(2527)	4.95	7.17

Table 9, Input impedance and vertical gain characteristics for Fig. 14's 46 m switched vee antenna where $\alpha = 0°$ and the ground's dielectric properties are $\epsilon_r' = 15$ and $\sigma = .008\ \Omega^{-1}/m$.

n	$Z_a(\Omega)$ at min. f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	max. f
1	57.8+j(424)	732+j(2748)	2.30	5.55
2	63.8+j(422)	827+j(2686)	2.54	5.59
3	69.8+j(417)	899+j(2591)	2.76	5.60
4	75.7+j(411)	960+j(2481)	3.01	5.62
5	81.6+j(406)	1018+j(2376)	3.26	5.75

Table 10, Input impedance and vertical gain characteristics for Fig. 14's 46 m switched vee antenna where $\alpha = 0°$ and the ground's dielectric properties are $\varepsilon_r' = 7$ and $\sigma = .001\ \Omega^{-1}/m$.

n	$Z_a(\Omega)$ at min. f	$Z_a(\Omega)$ at max. f	$G(0,\phi)$ (dB) at min. f	max. f
1	105+j(456)	1144+j(2622)	1.11	3.58
2	111+j(447)	1181+j(2503)	1.12	3.55
3	116+j(434)	1179+j(2382)	1.14	3.59
4	117+j(421)	1165+j(2269)	1.26	3.72
5	118+j(409)	1158+j(2174)	1.47	4.01



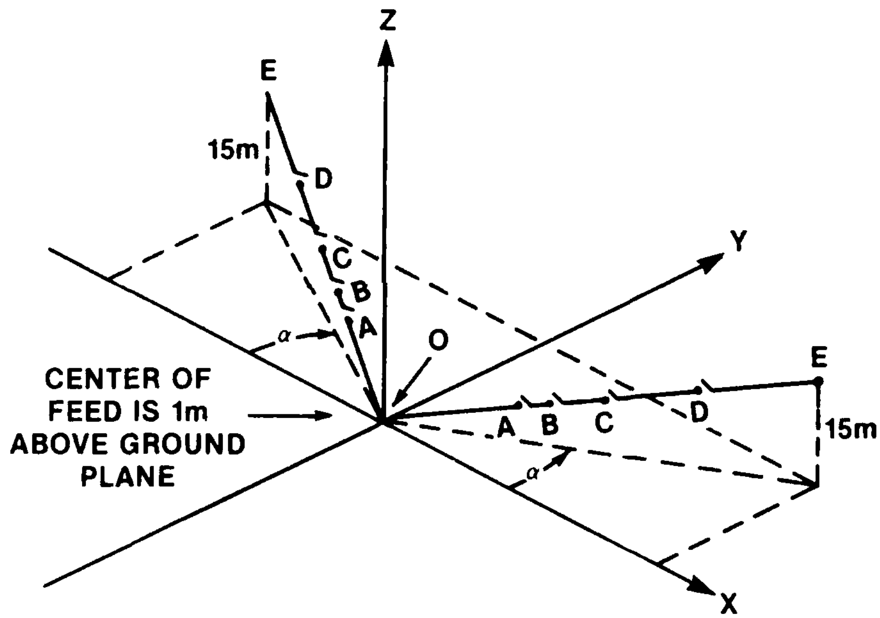


Fig. 14, Geometry associated with a 46 m switched vee antenna for the case where N = 5. The antenna wire lengths are; $\ell_1 = \ell_{OE} = 46.00$ m, $\ell_2 = \ell_{OD} = 33.34$ m, $\ell_3 = \ell_{OC} = 24.16$m, $\ell_4 = \ell_{OB} = 17.51$ m, and $\ell_5 = \ell_{OA} = 12.69$ m. Antenna wire diameter = .23 cm. The top surface of the ground is coincident with the XY plane.

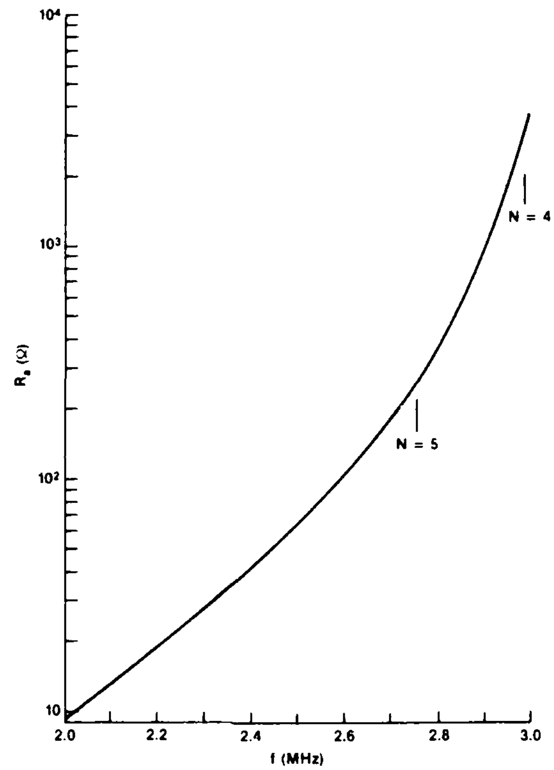


Fig. 15a, Input resistance (R_a)

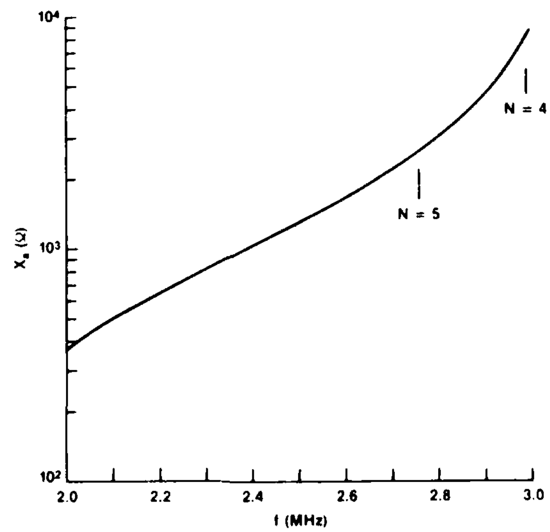


Fig. 15b, Input reactance (X_a)

Fig. 15, Input impedance ($Z_a = R_a + jX_a$) for Fig. 14's antenna where $\alpha = 0°$, the ground is considered to be perfectly conducting and the switches are in the n = 1 condition (see Table 6). Shown are the maximum frequencies in the n = 1 frequency sub-band when N = 4 and N = 5.

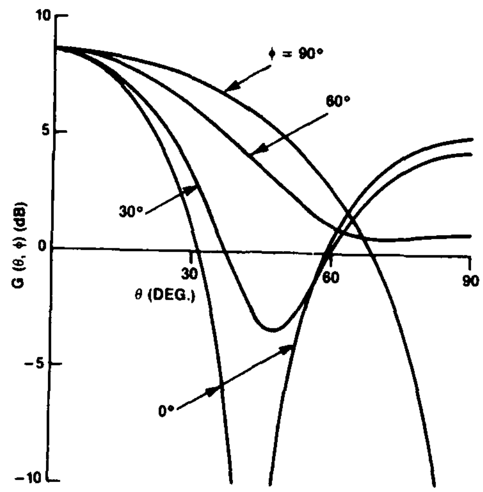


Fig. 16a, α = 0°

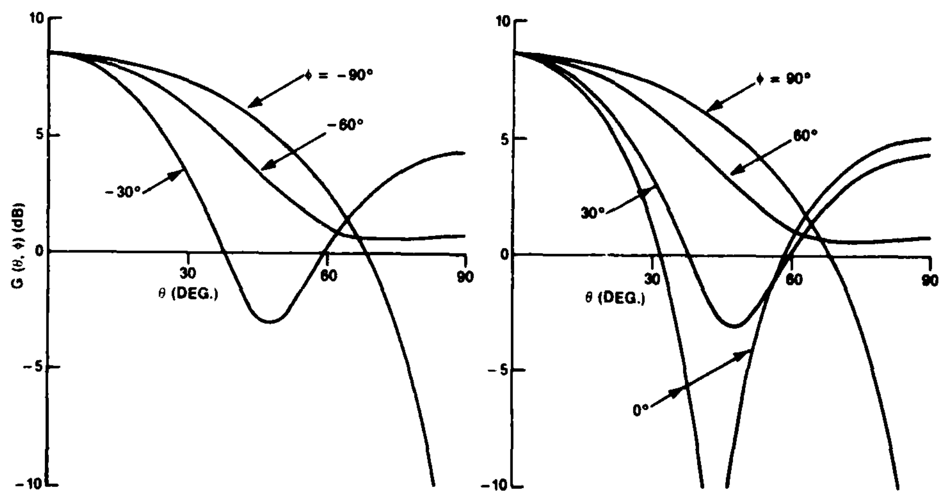


Fig. 16b, α = 10°

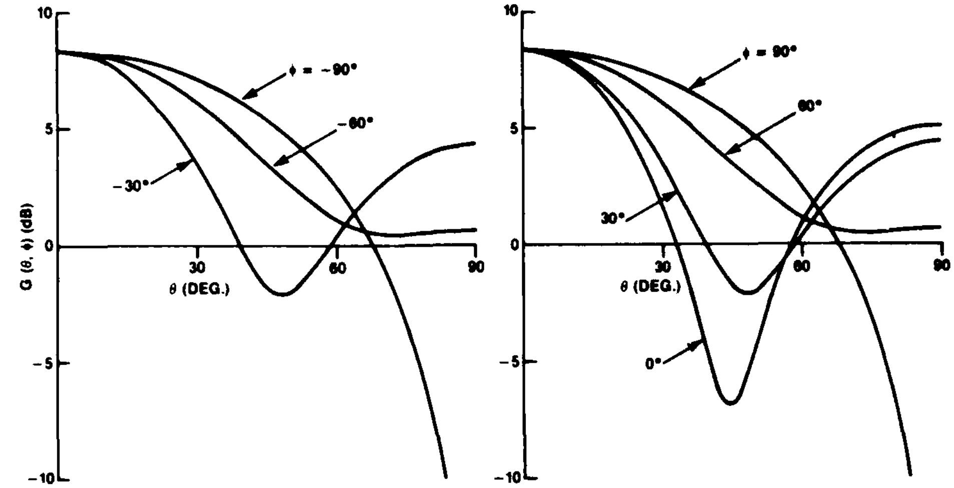


Fig. 16c, $\alpha = 20°$

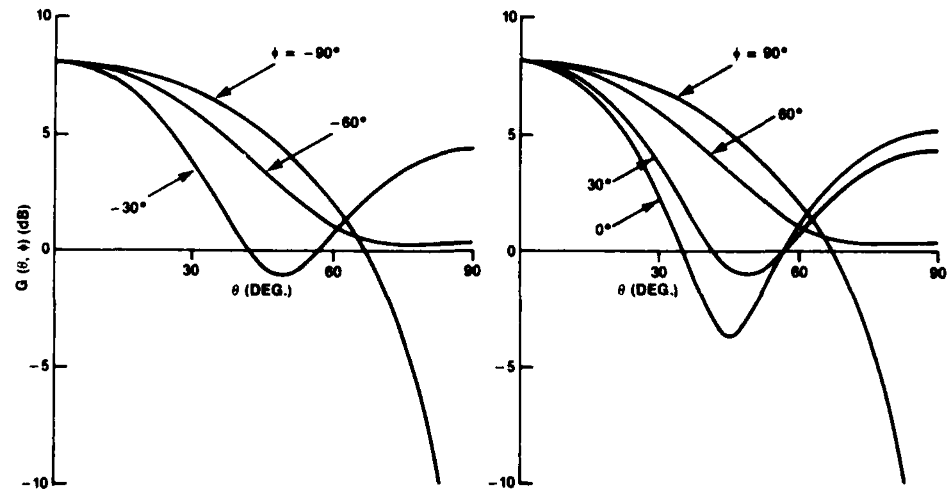


Fig. 16d, $\alpha = 30°$

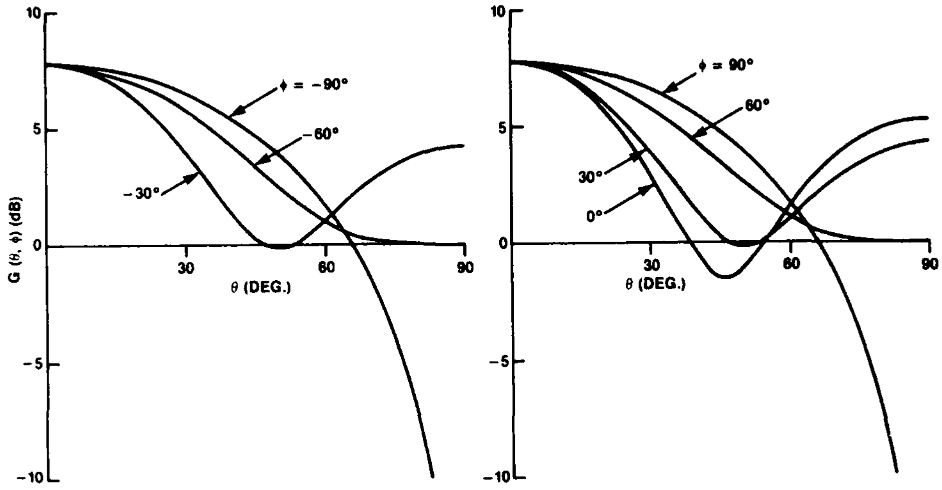


Fig. 16e, α = 40°

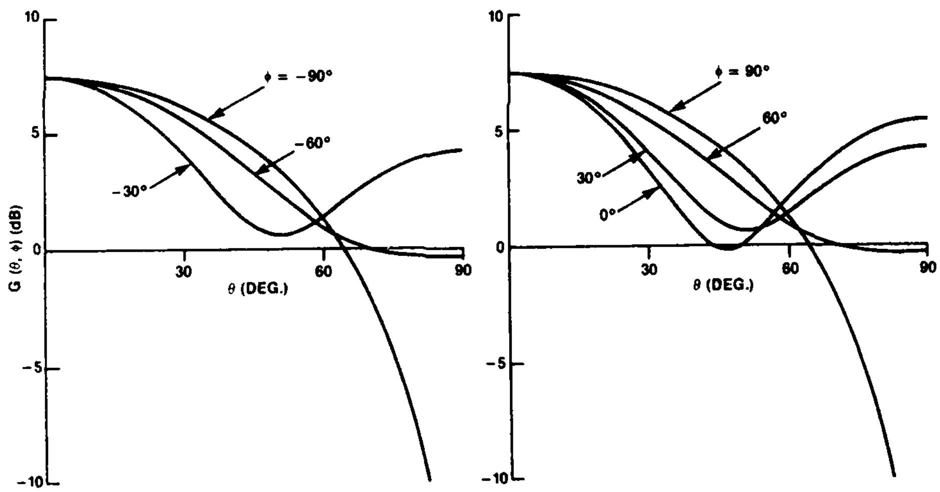


Fig. 16f, α = 50°

Fig. 16, Vertical gain patterns as a function of α for Fig. 14's antenna where f = 2.3797 MHz in the n = 1 frequency sub-band and the ground is perfectly conducting.

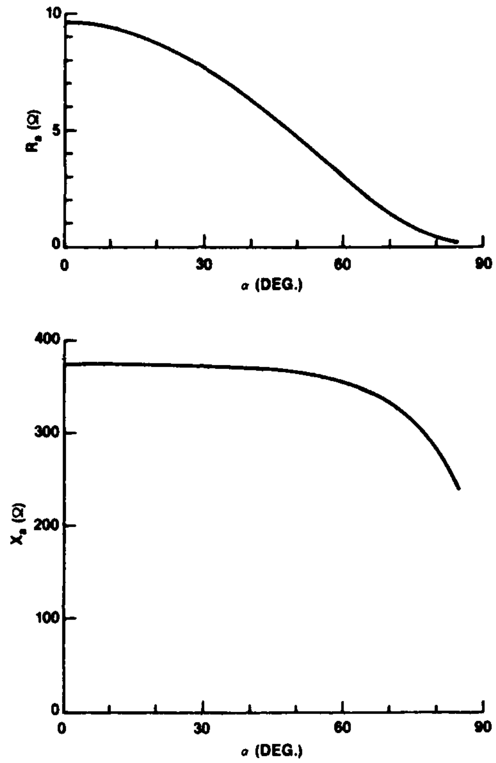


Fig. 17a, f = 2.0 MHz

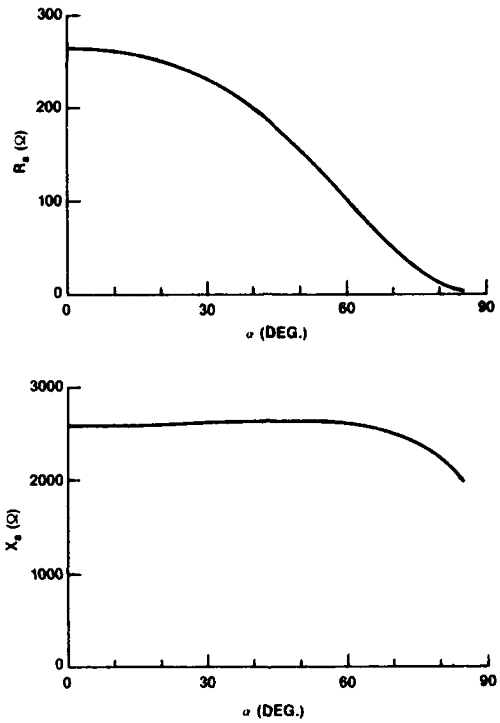


Fig. 17b, f = 2.7595 MHz

Fig. 17, Input impedance ($Z_a = R_a + jX_a$), for Fig. 14's antenna, as a function of α, at the minimum and maximum frequencies in the n = 1 frequency sub-band where the ground is perfectly conducting.

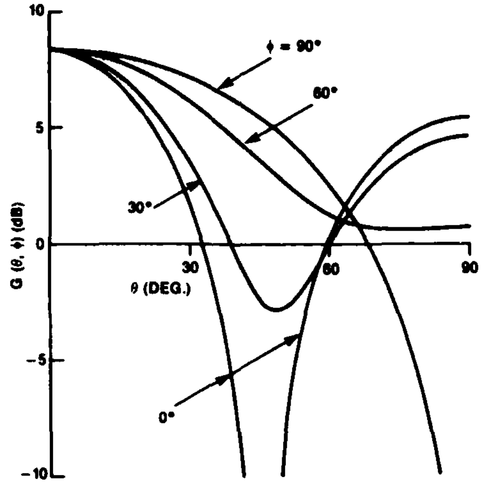


Fig. 18a, f = 2.0 MHz

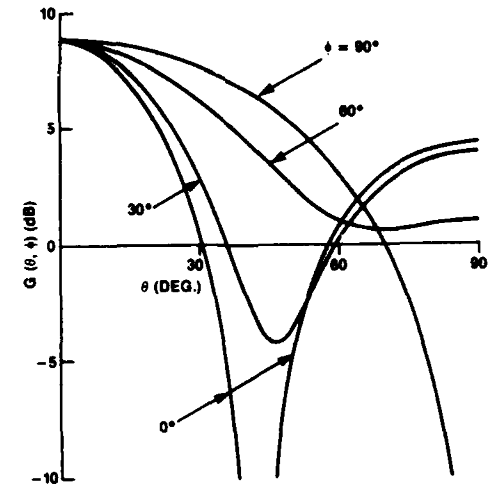


Fig. 18b, f = 2.7595 MHz

Fig. 18, Vertical total-gain patterns at the minimum and maximum frequencies in the n = 1 frequency sub-band for Fig. 14's antenna where α = 0° and the ground is perfectly conducting.

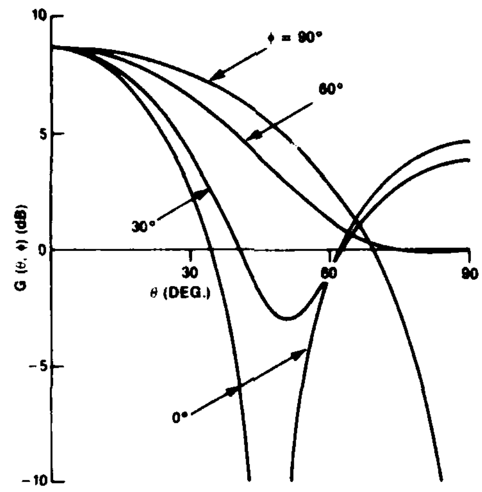


Fig. 19a, f = 3.8073 MHz

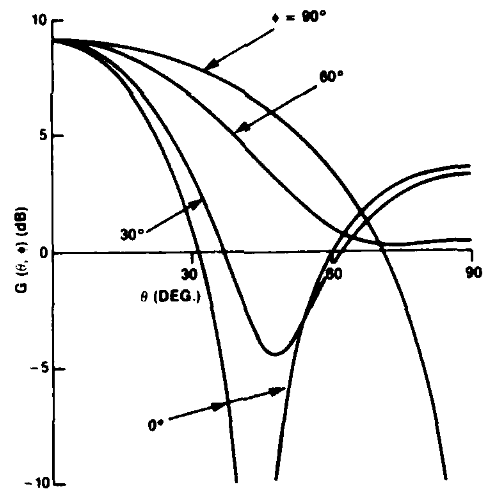


Fig. 19b, f = 5.2531 MHz

Fig. 19, Vertical total-gain patterns at the minimum and maximum frequencies in the n = 3 frequency sub-band for Fig. 14's antenna where α = 0° and the ground is perfectly conducting.

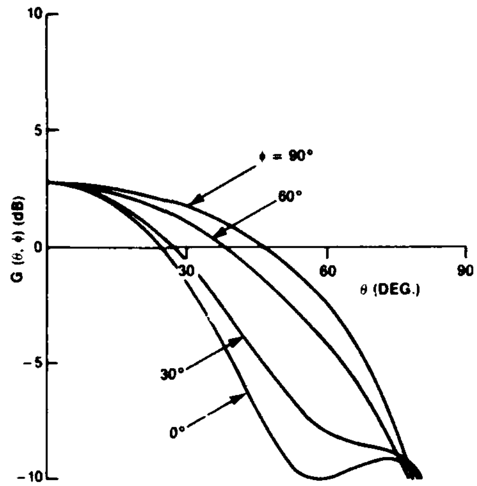


Fig. 20a, f = 3.8073 MHz

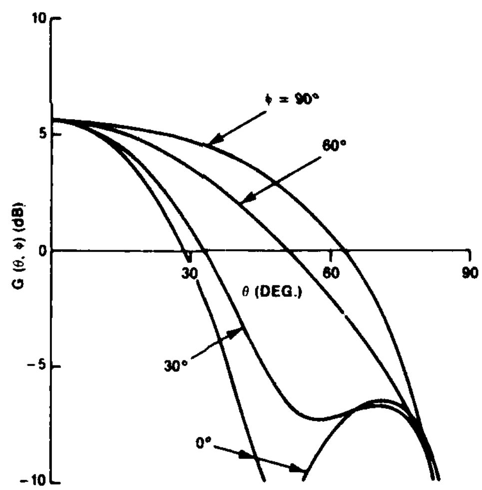


Fig. 20b, f = 5.2531 MHz

Fig. 20, Vertical total-gain patterns at the minimum and maximum frequencies in the n = 3 frequency sub-band for Fig. 14's antenna where $\alpha = 0°$ and the ground's dielectric properties are $\varepsilon_r' = 15$ and $\sigma = .008\ \Omega^{-1}/m$.

5. CONCLUSIONS

The scheme used for locating the antenna's switches was successful in that it divided the overall bandwidth of the antenna into sub-bands: a) with similar electrical properties, where in addition there are, b) no frequencies (such as antiresonant frequencies) at which it would be, for practical purposes, impossible to match the antenna to a transmission line.

The electrical characteristics of both the 46 m and 84 m switched vee antennas were significantly effected by the dielectric properties of the ground; in general the effect increased as the ground's conductivity was decreased from the perfect ground's infinity to .001 Ω^{-1}/m. In particular decreasing the ground's conductivity through the values indicated above: a) had little effect on the antenna's input reactance b) increased the antenna's input resistance (by factors of about three to five for the 84 m antenna, and two to ten for the 46 m antenna), and c) decreased the antenna's total vertical gain ($G(0,\phi)$) by up to about 8.5 dB for the 84 m antenna and 7.5 dB for the 46 m antenna. It was indicated that the above effects were local and could be substantially reduced by placement of a conducting screen on the ground below the antenna.

The large variation of antenna input impedance (with respect to both frequency and the ground's dielectric properties) means that the antenna tuning unit will have to be carefully designed.

The 84 m antenna, when compared with the 46 m antenna, has the following advantages: 1) its total gain beamwidth in the XZ plane can be significantly changed by varying α, and 2) it requires one fewer switches/leg. The substantially greater length of the 84 m antenna is its disadvantage. For the purpose of reducing sag in the 84 m antenna's wires, it will probably be necessary to locate towers between the antenna's extreme ends and the feed point.

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13. ABSTRACT

The characteristics of many antennas were investigated and evaluated against the general specification listed below. This document presents the properties of the two (switched vee) antennas which were judged to be best suited for the application.

Specification #1: The antenna is to serve as components for a 2 MHz to 10 MHz communications system where the signal's propagation path includes one reflection from the ionosphere and the separation between the transmitter and receiver is such that the signal's angle of incidence on the ionosphere is 50° or less.

Specification #2: The antenna's construction is to be such as to make it as easy, as is practical, to change the system's site.

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KEY WORDS

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Broadband (2 MHz to 10 MHz)
Switched Vee
Reflection from ionosphere

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